

Magnetic fingerprints of solar and stellar oscillations

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Abstract Waves connect all the layers of the Sun, from its interior to the upper atmosphere. It is becoming clear now the important role of magnetic field on the wave propagation. Magnetic field modifies propagation speed of waves, thus affecting the conclusions of helioseismological studies. It can change the direction of the wave propagation, help channeling them straight up to the corona, extending the dynamic and magnetic couplings between all the layers. Modern instruments provide measurements of complex patterns of oscillations in solar active regions and of tiny effects such as temporal oscillations of the magnetic field. The physics of oscillations in a variety of magnetic structures of the Sun is similar to that of pulsations of stars that posses strong magnetic fields, such as roAp stars. All these arguments point toward a need of systematic self-consistent modeling of waves in magnetic structures that is able to take into account the complexity of the magnetic field configurations. In this paper, we describe simulations of this kind, summarize our recent findings and bring together results from the theory and observations.

1 Introduction

Any turbulent medium, as the interior of the Sun or stars, generates sound. The basics of the theory excitation of sound waves by the turbulent flow were developed by Lighthill in 1952 [34]. Since then, a vast amount of theoretical and numerical efforts has been dedicated to specify the properties of the spectrum of sound waves generated in a stratified stellar convection zone, by improving the description of the turbulent energy spectrum of the convective elements *e.g.* [1, 13, 14, 38, 40, 52, 53]. Without going into details of these works, the present knowledge can be summarized in the following way. The efficiency of the energy conversion from convective to acoustic is proportional to a high power of the Mach number of the convective mo-

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tions ($M^{15/2}$ [13]). Most of the energy going into the p -modes, f -modes and propagating acoustic waves is emitted by convective eddies of size $h \sim M^{3/2}H$ (where H is the value of the pressure scale height), at frequencies close to the acoustic cut-off frequency $\omega \sim \omega_c$ and wavelengths similar to H . This defines the frequency dependence of the oscillation spectrum observed in the Sun and stars [13]. Since the Mach number is largest at the top part of the convection zone, the peak of the acoustic energy generation is located immediately below the photosphere [40, 53]. Recent numerical simulations of magneto-convection have shown that the magnetic field modifies the spectrum of waves [18]. Apart from the power suppression in regions with enhanced magnetic field, these simulations suggest an increase of high-frequency power (above 5 mHz) for intermediate magnetic field strengths (of the order of 300–600 G) caused by changes of the spatial-temporal spectrum of turbulent convection in a magnetic field.

Waves generated in the convection zone resonate inside a cavity formed by the stellar interior and the photosphere and are used by helio- and astroseismology to derive its properties [9, 57]. The information contained in the frequencies of the trapped wave modes is used by the classical helioseismology. A relatively newer branch called local helioseismology uses the information contained in the velocity amplitudes of the propagating waves measured in a region of interest on the solar surface (Duvall *et al.* [10]). By inversion of these measurements, variations of the wave speed and velocities of mass flows can be recovered below the visible solar surface. The inversion results have been obtained for quiet Sun regions as well as for magnetic active regions including sunspots. It is known that sunspots possess strong magnetic fields with a complicated structure in the visible layers of the Sun where the Doppler measurements used by local helioseismology are taken [50]. Consequently, such magnetic field can cause important effects on helioseismic waves, beyond the perturbation theories employed for helioseismic data analysis [2, 12, 29]. Recent numerical and analytical results demonstrate that the observed time-distance helioseismology signals in sunspot regions correspond to fast MHD waves [24, 37].

An estimation of the acoustic energy flux generated in the solar convection zone by the turbulent motions suggests that it can be as large as, e.g. $F_A = 5 \times 10^7$ ergs/cm²/s [38]. This is more than sufficient to maintain a hot chromosphere. It made the theory of acoustic heating of the upper atmosphere very attractive. However, soon after being proposed, the theory of acoustic heating encountered several major difficulties. It was found that both, low- and high-frequency waves are radiatively damped in the photosphere, reaching the upper layers with significantly less power [56]. An additional difficulty comes from the fact that the measured high-frequency acoustic fluxes in the photosphere and chromosphere are uncertain and non-conclusive [19, 59]. Low-frequency acoustic waves are reflected in the photosphere due to the effects of the cut-off frequency (~ 4 mHz) before reaching chromospheric heights. Due to their long wavelengths they have too large shock formation distances. Despite that, the five-minute waves with enough energy were detected in the chromosphere and corona of the Sun mainly above solar facular and network areas [5, 31, 35, 44, 58]. Several explanations of these waves involving the magnetic field have been recently proposed [20, 45]. The wave energy can reach the

upper layers not necessarily in the form of acoustic waves, but also in the form of other wave types, like magneto-acoustic waves, Alfvén waves or a family of waves propagating in thin magnetic flux tubes (see a recent example in *e.g.* [17]). All of them are related to the magnetic field structure. Osterbrock in 1961 [41] was the first to incorporate magnetic field into the theory of wave heating and to point out its importance on the propagation and refraction characteristics of the fast and slow MHD waves.

The above examples are only a few where the influence of the magnetic field on the wave properties is demonstrated to be important. Magnetic field not only changes the acoustic excitation rate and produces new wave modes. It also modifies the wave propagation paths and the direction of the energy propagation, it produces wave refraction and changes the reflection characteristics at the near-surface layers. Magnetic field defines the wave propagation speeds and changes the acoustic cut-off frequency. It can also change the wave dissipation rates and provides an additional energy source. Magnetic field connects all the atmospheric layers facilitating the channeling of waves from the lower to the upper atmosphere. This makes the magnetic field an important ingredient the theories of the wave propagation in the atmospheres of the Sun and stars.

Apart from the problems set by the local helioseismology in magnetic regions and the wave heating theory, of pure physical interest is the interpretation of oscillations observed in different magnetic structures in terms of MHD waves. For example, the wave dynamics seen in high-resolution DOT movies of a sunspot region [48] demonstrate that phenomena such as chromospheric umbral flashes and running penumbral waves are closely related. What type of waves are responsible for them? Solar small-scale and large-scale magnetic structures have distinct magnetic and thermal properties and support different wave types. The observed frequency spectrum of waves in these structures is not the same (see the introduction in [23]). Numerical simulations of waves in non-trivial magnetic structures (*e.g.* [4, 15, 16, 21, 23, 47]) have shown the complex pattern formed by waves of various types that can propagate simultaneously in various directions. Different wave modes can be detected in observations depending on the magnetic field configuration and the height where acoustic speed, c_S , and Alfvén speed, v_A , are equal relative to the height of formation of the spectral lines used in observations.

During the last years we applied efforts to develop a numerical code aimed at calculating the non-linear wave propagation inside magnetic fields in 2 and 3 dimensions. Using this code we focused our analysis on several problems described above, namely: magneto-acoustic wave propagation and refraction in sunspots and flux tubes; channeling the five-minute photospheric oscillations into the solar outer atmosphere through small-scale magnetic flux tubes; influence of the magnetic field on local helioseismology measurements in active regions. The results of these studies are published in [20, 21, 23, 24]. In the rest of the paper we briefly summarize the results and conclusions of these works. In addition, the last section gives our recent contribution to the problem of the interpretation of observations of waves in magnetic roAp stars.

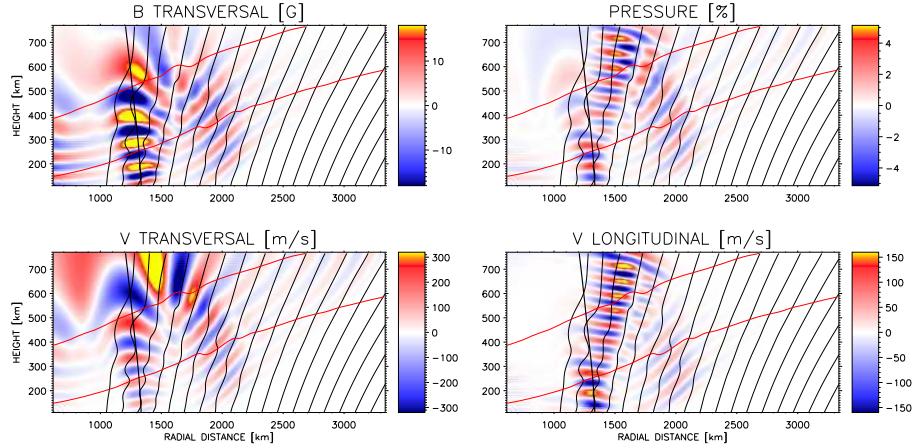


Fig. 1 Variations of the velocity, magnetic field and pressure at an elapsed time $t = 100$ sec after the beginning of the simulations. In each panel, the horizontal axis is the radial distance X from the sunspot axis and the vertical axis is height from the photospheric level. The black inclined lines are magnetic field lines. The two more horizontal lines are contours of constant c_S^2/v_A^2 , the thick line corresponding to $v_A = c_S$ and the thin line to $c_S^2/v_A^2 = 0.1$. Top left: transversal variations of the magnetic field. Top right: relative pressure variations. Bottom panels: transversal and longitudinal variations of the velocity.

2 Waves in sunspots

Sunspots show a very complex dynamics as revealed by high-resolution observations. The umbral flashes observed in the chromosphere are thought to be acoustic shock waves [48] propagating along the nearly vertical magnetic field lines. The visible perturbation then expands quasi-circularly out to the penumbra producing the running penumbral waves [54]. This visible pattern can be interpreted as slow (acoustic) wave propagating along the inclined magnetic field lines in the penumbra [3]. The power distribution at different frequencies in active regions is rather complex as well. The recent observations of HINODE [39] confirmed the conclusions done with the ground-based observations (see *e.g.* Tziotziou [55]) that the dominating frequency of oscillations within a sunspot depends on the position in the umbra or penumbra, as well as on the height in the atmosphere. In the chromosphere the greatest power is observed in the umbra at 5–6 mHz and a sharp transition between umbra and penumbra where the dominating frequency is 3 mHz. In the umbral photosphere the oscillation power is generally suppressed compared to the quiet photosphere, except for the excess of low-frequency power at 1–2 mHz at the umbra-penumbra boundary. An unknown question is what drives the oscillations observed in sunspots? Are these waves due to a resonant response of the sunspot flux tube to the external driving by p -modes? Are there sources of oscillations inside the magnetized regions?

In the simulations described below we aim at identifying the types of waves modes observed in different layers of a sunspot atmosphere. We supposed a source of high-frequency (100 mHz) monochromatic waves located at photospheric level inside the umbra where the acoustic speed is slightly larger than the Alfvén speed. The waves are assumed to be linear. The initial unperturbed magnetostatic sunspot model was evaluated following the strategy described in [42] with a maximum magnetic field strength of 2.2 kG and characteristic radius of 6 Mm. The simulation domain is 2-dimensional, extending 0.86 Mm in the vertical and 3.5 Mm in the horizontal directions.

A snapshot of the simulations is given in Fig. 1. The source generates a set of fast magneto-acoustic waves propagating upwards. After the perturbation reaches the height where $c_S = v_A$ the mode transformation takes place. The fast (acoustic) mode propagating vertically below $c_S = v_A$ level is transmitted as fast (magnetic) mode in the $c_S < v_A$ region (visible in the transversal velocity). Its wavelength increases with height due to the rapid increase of the Alfvén speed. The left part of the wave front of the fast mode (closer to the axis) propagates faster than its right part (farther from the axis) which produces its reflection back to the photosphere at some height above the $c_S = v_A$ level. The same happens to the other fast mode propagating to the left, except that this fast wave refracts toward the sunspot axis. A part of the original fast (acoustic) mode energy is transformed to the slow (acoustic) mode in the $c_S < v_A$ region. The slow mode is visible in the longitudinal velocity snapshots. It propagates with a lower speed, close to the local speed of sound. This slow mode is channeled along the magnetic field lines higher up to the chromosphere increasing its amplitude. A similar behaviour is observed in simulations with an initial condition in the form of an instantaneous pressure pulse rather than a monochromatic wave. From these simulations we conclude that in sunspots only a small fraction of the energy of the photospheric pulse can be transported to the upper layers, since an important part of the energy is returned back to the photosphere by the fast mode. Above a certain height in the low chromosphere, only slow (acoustic) modes propagating along the magnetic field lines can exist in the umbra defining the dominating frequency of waves according to the cut-off frequency of the sunspot atmosphere.

3 Waves in small-scale flux tubes

Acoustic waves propagating vertically in the quiet solar atmosphere change their dominating frequency with height from 3 mHz in the photosphere to 5 mHz in the chromosphere. An explanation for this effect was suggested by Fleck & Schmitz [11], who argue that this is a basic phenomenon due to resonant excitation at the atmospheric cut-off frequency. The low temperatures of the high photosphere give rise to a cut-off frequency around 5 mHz. However, numerous observations suggest that there is no such change for waves observed in chromospheric and coronal heights above solar facular and network regions [5, 31, 35, 44, 58]. What are the mechanisms that allow the 3 mHz waves (evanescent in the photosphere) to propagate

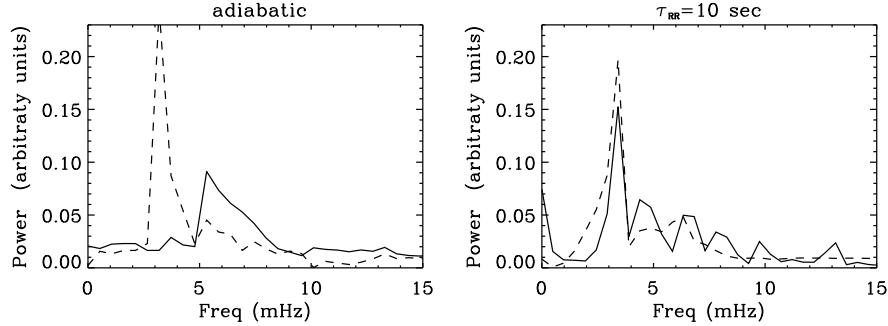


Fig. 2 Left: photospheric at 400 km (dashed line) and chromospheric at 1500 km (solid line) power spectra for adiabatic simulations of waves in flux tubes. Right: same but for simulation with radiative relaxation time τ_{RR} equal to 10 s.

up to chromospheric heights? De Pontieu *et al.* [45] suggest that the inclination of magnetic flux tubes in facular regions is essential for the leakage of p -modes strong enough to produce the dynamic jets observed in active region fibrils. However, this mechanism is hardly to be at work in the photosphere, where the plasma β is larger than 1 and the acoustic waves do not have a preferred direction of propagation defined by the magnetic field. In addition, it can not easily explain the observations of vertically propagating 3 mHz waves in facular and network regions at chromospheric heights. Alternatively, a decrease in the effective acoustic cut-off frequency can be produced by radiative energy losses in thin flux tubes (Roberts [46]).

We explored the latter mechanism and extended the theoretical analysis of Roberts [46] by means of non-adiabatic, non-linear 2D numerical simulations of magneto-acoustic waves in small-scale flux tubes with a realistic magnetic field configuration. The simulations are obtained by introducing a 3 mHz harmonic vertical perturbation at the axis of a magneto-static flux tube. Radiative losses were taken into account by means of Newton's law of cooling with a fixed value of the radiative relaxation time τ_{RR} . We compare two identical simulation runs that differ only by the value of τ_{RR} . The first run is in adiabatic regime ($\tau_{RR} \rightarrow \infty$) and the second run has $\tau_{RR} = 10$ s constant through the whole atmosphere. The magnetostatic flux tube model is constructed after the method of Pneuman *et al.* [43] with a maximum field strength of 740 G and radius of 100 km in the photosphere. The simulation box extends 2 Mm in the chromosphere. The details of these simulations are explained in [20, 23].

The vertical photospheric driver generates a fast magneto-acoustic wave. This wave propagates upwards through the $c_S = v_A$ layer, preserving its acoustic nature and being transformed into a slow magneto-acoustic wave higher up. An essential feature of these simulations is that the wave perturbation remains almost complete within the same flux tube. Thus, it can deposit effectively the energy of the driver into the chromosphere. The power spectra of oscillations resulted from simulations at two heights in the photosphere and the chromosphere are displayed in Fig. 2. In the adiabatic case (left panel) there is a shift of the dominating frequency in the

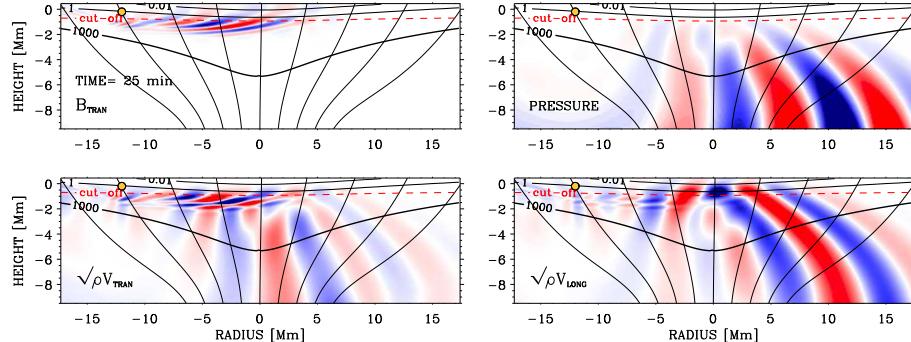


Fig. 3 Top left: transversal magnetic field variations. Top right: pressure variations. Bottom panels: transversal and longitudinal velocity variations. The snapshot is taken 25 min after the start of the simulations with $B_{\text{phot}} = 1.5$ kG. The dots mark the location of the source. The velocities are scaled with a factor $\sqrt{\rho_0}$. Black contours of constant c_s^2/v_A^2 are marked with numbers. The dashed contour marks the position of the cut-off height for 3 mHz waves. Black inclined lines are magnetic field lines. Negative heights correspond to sub-photospheric layers.

oscillation spectra from 3 mHz in the photosphere to 5 mHz in the chromosphere. In contrast, there is no such shift in the case of $\tau_{RR} = 10$ s (right panel). The latter power spectra look very similar to those obtained from spectropolarimetric observations of a facular region by Centeno *et al.* [5]. It confirms that radiative losses play an important role in small-scale magnetic structures, such as those present in facular regions and are able to decrease the cut-off frequency and modify the transmission properties of the atmosphere.

4 Local helioseismology in magnetic regions

Time-distance helioseismology is a branch of local helioseismology that makes use of wave travel times measured for wave packets traveling between various points on the solar surface through the interior. The inversion of these measurements is done under the assumption that the variations of the travel times are caused by mass flows and wave speeds below the surface [10, 27, 28, 30, 60]. The interpretation of results of time-distance seismology encountered major critics when applied to magnetic active regions of the Sun. Magnetic field in active regions modifies the wave propagation speeds and directions making difficult to separate magnetic and temperature effects (see *e.g.* [36]). To understand the influence of the magnetic field on travel time measurements, forward modeling of waves in magnetic regions is required. This has become the preferred approach in recent years.

With this aim, we performed 2D numerical simulations of magneto-acoustic wave propagation through a series of model sunspots with different field strength, from the deep interior to chromospheric layers [22]. The waves are excited by an

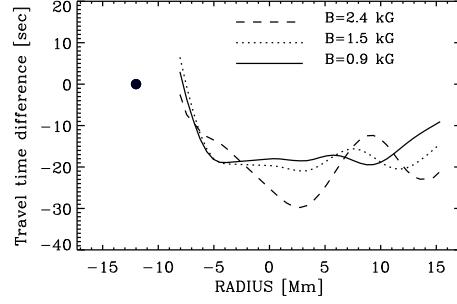


Fig. 4 Phase travel-time difference calculated between the travel times measured in simulations without magnetic field and simulations with different model sunspots (indicated in the figure) as a function of horizontal distance. The source location at $X_0 = 12$ Mm to the left of the sunspot axis is marked by a circle.

external force localized in space just below the photosphere at -200 km, according to the models of wave excitation in the Sun [40, 53]. The spectral properties of the source resemble the spectrum of solar waves with the maximum power at 3.3 mHz. In the experiment described below the source is located at 12 Mm far from sunspot axis in the region where the acoustic speed is slightly larger than the Alfvén speed. The details of the numerical procedure are given in [24].

The magneto-static sunspot models are calculated using the method proposed in [22]. The sunspot models have a cool zone below the surface down to, about, -2 Mm depth. Below this depth the temperature gradient in horizontal direction is small and no hot zone is introduced in the present study. The photospheric field strength in three models used is of $B_{\text{phot}}=0.9, 1.5$ and 2.4 kG.

Fig. 3 shows a snapshot of the simulations. The fast magneto-acoustic modes (analog of p -modes in the quiet Sun) can be distinguished propagating below the surface in the pressure and velocity variations. In addition, there is a perturbation with much smaller vertical wavelength visible best in the magnetic field and transversal velocity variations. A part of this perturbation is a slow MHD mode generated directly by the source at horizontal position $X = -12$ Mm. This mode propagates with a visibly low speed downwards along the sunspot magnetic field lines. In addition to the slow MHD waves generated directly by the source there is another wave type. The propagation speed of this small vertical wavelength disturbance is comparable to that of the fast modes. Unlike the slow MHD waves, these waves propagate horizontally across the sunspot. We conclude that these waves are magneto-gravity waves. The variations produced by these magneto-gravity waves decrease rapidly with depth and disappear almost completely below -3 Mm (top left panel of Fig. 3).

What are the surface signatures of these modes and how do they affect the travel time measurements in solar active regions? As follows from the bottom right panel of Fig. 3, in the photospheric layers the dominant variations of the longitudinal (vertical) velocity are due to the fast magneto-acoustic mode propagating horizontally across the sunspot. Fig. 4 gives the travel time differences between the phase travel times of the this mode measured in the sunspot photosphere relative to the non-magnetic quiet Sun. The latter is represented by standard solar model S [6]. The

travel times are obtained from a Gabor's wavelet fit to the simulated time-distance diagrams. Negative values mean that waves in the magnetic simulations propagate faster. Here, it must be recalled that the model sunspots have a cool zone below the photosphere implying a lower acoustic speed. Thus, if the waves were purely acoustic in nature the travel time differences in Fig. 4 would have positive sign. Instead the propagation speed of the fast magneto-acoustic waves increases with the magnetic field, which has the natural consequences observed in Fig. 4: the waves in sunspot models with larger magnetic field propagate faster. The values of the travel times differences that we obtain from simulations agree rather well with those measured in solar active regions (see *e.g.* [7]). Thus, we conclude that the wave propagation below solar active regions is governed by the magnetic field. Despite the new wave modes generated in the sunspot atmosphere do not affect directly the time-distance helioseismology measurements, the travel times of the fast MHD modes (analog of the *p*-modes) are affected by the magnetic field. A more complete analysis of these simulations is presented in [24].

5 Oscillations in magnetic roAp stars

Closely related to the problems of local helioseismology in magnetic regions is the problem of interpreting the oscillations in magnetic rapidly oscillating peculiar Ap stars. These stars posses a strong dipolar-like magnetic field of 1–25 kG and horizontal and vertical stratification of chemical composition. They pulsate with periods between 4 and 20 minutes. This offers a unique opportunity to study the interaction between convection, waves and strong magnetic field. Recent reviews on the prop-

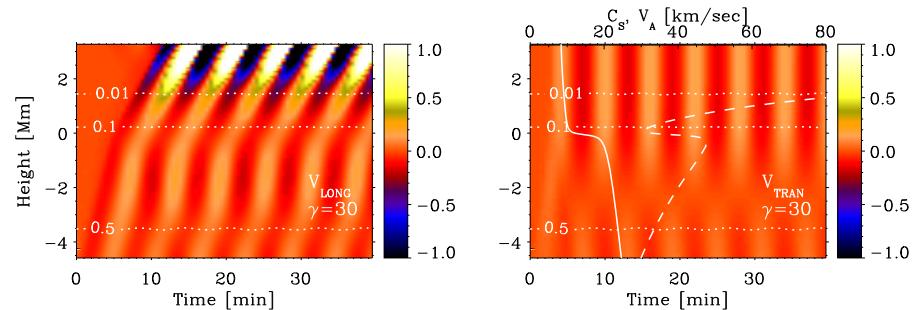


Fig. 5 Variations of the longitudinal (left) and transversal (right) velocities with height and time in a roAp star with $T_{\text{eff}} = 7750$ K and $\log g = 4.0$. The units are km/sec. Results are for a dipolar magnetic field strength $B = 1000$ G, at a latitude where the inclination with respect to the local vertical is 30 degrees and oscillation frequency 2.8 mHz. Zero height corresponds to the bottom photosphere. Contours of constant c_S^2/v_A^2 are plotted with dotted lines. Height dependences of the c_S (solid line) and v_A (dashed line) are plotted over the right panel, the scale is given by the upper axis.

erties of these stars and their pulsations can be found in Kurtz [33], Cunha [8] and Kochukhov [25, 26].

Several properties of the oscillations observed on these stars make them peculiar. The amplitudes of the pulsations vary with rotation period according to the magnetic field structure giving rise to oblique pulsator model [32]. The spectral lines of different chemical elements pulsate with order of magnitude different amplitudes and significant phase shifts between them, depending on their formation heights [49]. In addition, several stars pulsate with frequencies exceeding the acoustic cut-off predicted by stellar models [51]. Due to their strong magnetic fields, the atmospheres of roAp stars are regions where the magnetic pressure exceeds the gas pressure and the oscillations are magnetically dominated. Recent analytical modeling of high-frequency waves [51] suggest that the pulsations observed in the atmospheric layers can be a superposition of running acoustic waves (slow MHD) and nearly standing magnetic waves (fast MHD) that are nearly decoupled in the region $\beta \ll 1$.

In order to identify the wave modes observed in the atmospheres of roAp stars, we solved numerically the governing non-linear MHD equations in 2D geometry for a semi-empirical model atmosphere. The model has $T_{\text{eff}} = 7750$ K and $\log g = 4.0$. We assumed that: (1) magnetic field varies on spatial scales much larger than the typical wavelength, allowing the problem to be solved locally for a plane-parallel atmosphere with a homogeneous inclined magnetic field; (2) waves in the atmosphere are excited by low-degree pulsation modes with radial velocities exceeding horizontal velocities. We studied a grid with the magnetic field strength B varying from 1 to 7 kG, its inclination varying between 0 and 60 degrees and pulsation frequencies between 1.25 and 2.8 mHz (below and above the cut-off frequency of this simulated star).

Despite the simple magnetic field geometry, the simulations give rise to a complex picture of the superposition of several modes, varying significantly depending on the parameters of the simulations. An example of the velocity field developed in the simulation with $B = 1$ kG, $\gamma = 30$ degrees and pulsation period $T_0 = 360$ sec is given in Fig. 5. Longitudinal and transversal projections of the velocity with respect to the local magnetic field allow us to separate clearly the wave modes. The longitudinal velocity component shows the presence of the slow MHD (acoustic) wave. Under $\beta \ll 1$ conditions, this wave is propagating along the inclined magnetic field. The transversal velocity reveals the fast MHD (magnetic) wave. The rapid increase of the Alfvén speed with height makes the wavelength of this mode extremely large occupying the whole atmosphere. While at the bottom layers (below the photosphere) the amplitudes of the fast and slow modes are comparable, in the upper atmosphere the slow mode clearly dominates since its amplitude increases exponentially with height, much more than that of the fast mode. Two node heights can be observed in the case of the slow mode (at -3.5 and 0 Mm) and one node height in the case of the fast mode (at -2 Mm), all produced by wave reflection. The model atmosphere used in the simulations has strong density and temperature jumps at the photospheric level, producing efficient reflection. We can observe an evanescent pattern of the slow mode at heights between -3 and 0 Mm (left panel of Fig. 5). Below and above these heights the slow wave is propagating with a speed

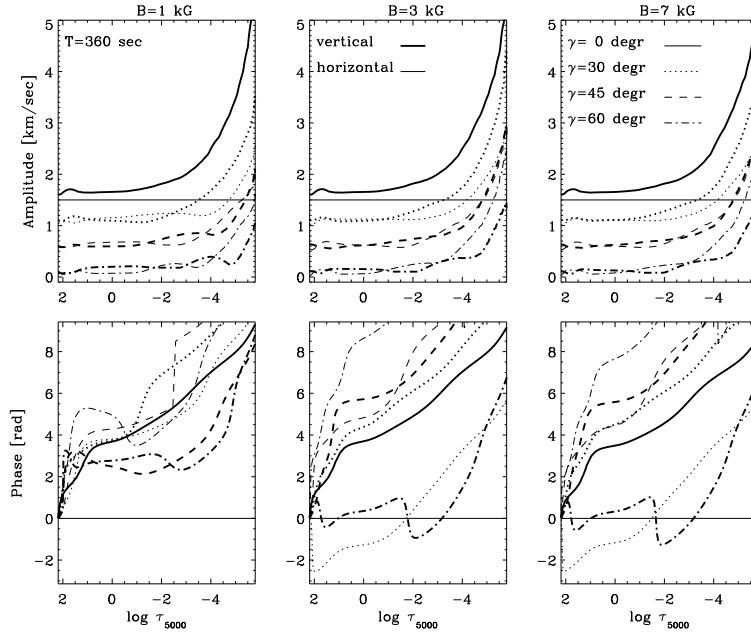


Fig. 6 Amplitudes (top) and phases (bottom) of the vertical (thick lines) and horizontal (thin lines) velocities as a function of optical depth in the atmosphere of a roAp star obtained from the simulations with dipolar magnetic field of different strength B and at different latitudes corresponding to inclinations γ (indicated in the figure). The results are for the oscillation frequency 2.8 mHz. The amplitude curves for each γ are separated by 0.5 km/sec for better visualization.

defined by the local speed of sound. One can appreciate a considerably slower propagation in the upper layers due to the smaller sound speed. Strong slow wave shocks are formed above 2 Mm height with amplitudes up to 5 km/sec. The amplitudes of the velocities obtained in the simulations are similar to those observed [25].

Fig. 6 gives the amplitudes and phases of the horizontal and vertical velocities as a function of the optical depth for different field strengths and inclinations obtained in the simulations with the pulsation period of 360 sec. The superposition of the fast and slow waves produces additional node-like structures at heights where these modes interfere destructively. Fig. 6 shows that both amplitudes and phases of the velocity are complex functions of optical depth and of the parameters of the simulations. In general, the amplitude of the vertical velocity decreases with the inclination, while the amplitude of the horizontal velocity increases. In the case of the inclination $\gamma \neq 0$, the amplitudes of the waves at the top of the atmosphere are smaller for $B = 1$ kG compared to larger field strengths. This can be explained by the decrease of the cut-off frequency due to preferred wave propagation in the direction of the magnetic field [46]. The location of the node-like surfaces and waves propagating up and down at different heights can be appreciated from the phase curves at the bottom panels of Fig. 6. All these features are similar to observations.

The disc-integrated velocity signal produced by the atmospheric pulsations of such a star would depend in a complex way on the inclination of the magnetic axis with respect to the observational line of sight and needs a further study. However, we can conclude that the velocity signal observed in the upper atmospheric layers of roAp stars is mostly due to running slow mode acoustic waves. The node structures and the rapid phase variations at the lower atmospheric layers are due to multiple reflections and interference of the slow and fast MHD wave modes.

6 Conclusions

Magnetic field introduces an additional restoring force and makes the propagation of waves in stellar atmospheres more complex compared to the case of acoustic-gravity waves. We have developed a numerical code that allows the modeling of waves inside magnetic fields for a large variety of phenomena, from Sun to stars. We have applied this code to study the role of different solar magnetic structures concerning wave energy transport to the upper atmosphere; interpretation of local helioseismology measurements in solar active regions; pulsations of magnetic roAp stars. Puzzling physics of the interaction of waves with the magnetic field in a variety of magnetic field configurations in the Sun and stars is to be explored in the future.

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